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ABSTRACT

Alouette-II electrostatic probe measurements of the nighttime electron temperature (T_e) and concentration (N_e) in the height range 2500 ± 500 Km are presented on global basis (-60 to +60 geomagnetic latitude). The major feature of the protonosphere at this altitude is an electron temperature trough of the order of 1800°K at the low latitudes, increasing sharply to over 3000°K at the middle latitudes. The electron concentration exhibits a pair of maxima at about 30° north and south with values ranging from 4×10^3/cc in fall to 8×10^3/cc in local summer. No definitive seasonal dependence is apparent in T_e. Comparison of the present Alouette-II measurements with nearly simultaneous measurements on Explorer XXII during summer 1966 reveal a field aligned positive temperature gradient in T_e. Typical gradients at 1000 Kilometers are 0.5°/Km on the 35° field line and 1.0°/Km on the 50° field line. These gradients are consistent with the thermal energy stored in the nocturnal protonosphere and therefore no external source of heat is required to explain the observations.

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INTRODUCTION

In November 1965 the Alouette-II satellite was launched into a near-polar orbit (80°) having an apogee altitude of 3000 Km and perigee altitude of 500 Km. In addition to the topside sounder experiment and other instruments carried by the satellite (Nelms et al, 1966), the Alouette-II employs cylindrical electrostatic probes for the measurement of electron temperature (T_e) and concentration (N_e).

Owing to the near synchronism between the orbital precession rate and the apsidal rotation rate, apogee tended to remain on the nightside of the orbit, and conversely perigee remained on the dayside, during the early years of the Alouette-II lifetime. When apogee was near the equator, an event which occurred at three month intervals, the satellite remained in the protonosphere (2500 ± 500 Km) throughout nearly its entire pole to pole passage (60° N to 60° S). In this paper we present the latitudinal profiles of T_e and N_e corresponding to four such periods in the summer, fall and winter of 1966 and in the spring of 1967. We also relate the summer data to nearly simultaneous measurements by the same experiment on Explorer XXII, which was in a 1000 Km circular orbit having the same near polar inclination. From these data we derive the temperature gradients and electron scale heights between these two levels. We also compare

the measured N_e at the Alouette-II altitude with that calculated under hydrostatic equilibrium from the observed temperature and temperature gradient, assuming that protons are the only ions present at these altitudes.

THE EXPERIMENT

The cylindrical probes employed on Alouette-II are identical to those on several earlier satellites including Explorer XVII (Brace et al, 1965), Explorer XXII (Brace and Reddy, 1965), and Tiros VII (Reddy et al, 1967). The particular experimental arrangement employed on Alouette-II has been described by Findlay and Brace (1968). The principle of operation is well known. A cylindrical collector is mounted at an appropriate position on the surface of the satellite and protrudes into the ionospheric plasma which is to be measured. The potential of the collector is swept through the range of -3 to +10 volts relative to the satellite, which first repels and then attracts the thermal electrons. The amplitude of the electron saturation current is proportional to the electron concentration, and the shape of the waveform in the electron retardation region is a measure of the electron temperature (Mott-Smith and Langmuir, 1926; Spencer et al, 1965).

Two probes were used to assure nonwake measurements at all times. The mounting position of the probes and the electronic system employed in the measurement is shown schematically in Figure 1. The portion of the sensor nearest the satellite is an 9-inch guard electrode which is driven at the same potential as the collector itself, but only the current to the collector is measured.

Four linear ranges of sensitivity are employed to resolve the currents: 2×10^{-8}, 1.5×10^{-7}, 1.0×10^{-6}, and 8×10^{-6} amperes full scale. These sensitivities permit the resolution of electron concentration in the range of 50/cc to 4×10^5/cc. Since the current in the electron retardation region is much smaller than the saturation current, T_e can only be resolved when N_e exceeds about 5×10^2/cc.

The relative accuracy of N_e varies with current resolution corresponding to the particular pass but is typically of the order of 5% (Brace et al, 1968). The absolute accuracy is about 10% (Donley et al, 1968). The absolute accuracy of T_e on the other hand is probably better than 10% (Brace et al, 1968). Although the relative accuracy of T_e can be better than 2% when this precision is necessary, the quality of the analog film records available for this morphological study permit only about 5% relative accuracy.

RESULTS

The satellite was commanded-on for 13 minute intervals about 20 times per day, most of these over STADAN telemetery stations distributed about the world as shown in Figure 2. Data recorded at Canadian and British telemetery stations have not been employed.

Figure 3 shows the relationship between the altitude and local time encountered along the Alouette-II orbits during one of the periods employed in this study. It can be seen that when apogee is near the equator (an event which occurs at three month intervals) the satellite remains in the protonosphere throughout its nightside passage from 60° N to 60° S. The corresponding local time of

the orbit remains at approximately 0100 hours during this week and thus represents typically the nighttime conditions. Four such periods (three during 1966 and one during early 1967) have been used to obtain the latitudinal profiles of T_e and N_e from the observed volt-ampere characteristics. Figures 4a through 4d show plots of actual T_e and N_e values for the periods May 15-22, Aug. 24-31, Dec. 1-8, 1966 and Mar. 1-8, 1967 respectively. The data points are obtained at about 2-minute intervals during each pass. This corresponds to increments of 5° of latitude. The individual points from each pass are joined by straight lines to represent the instantaneous latitudinal structure existing, as well as to identify all the points belonging to the same pass.

The altitude assigned to the measurements in these figures is 2500 ± 500 Km. Although the altitude of the measurements was changing rapidly at the extreme latitudes (see Figure 3), the latitudinal N_e plots are probably not greatly distorted because of the large electron scaleheights.

Latitudinal Variations at 2500 Km

The gross latitudinal structure of the nighttime protonosphere can be gathered from Figures 4a through 4d. The electron temperature exhibits a wide trough at low latitudes, with values varying between 1500 and 2000°K and rising sharply to over 3000°K at midlatitudes. The electron concentration shows a minimum at the equator and two broad maxima at about 30° north and south. The value of N_e at the equatorial trough is, on the average, about 20% lower than at the maxima. At latitudes above 30°, a strong decrease in N_e is apparent; the

electron concentration decreasing by an order of magnitude between 40° and 60°. The resulting minimum at 60° seems to correspond with the main trough pointed out by Muldrew (1965) from Alouette-I data and coincides with the position of the plasmapause during magnetically quiet periods (Taylor et al, 1965).

Magnetic Disturbance Effects

It should be pointed out that the measurements presented in Figures 4a-4d are for magnetically quiet periods with the 3-hour magnetic index a_p less than 18. However, during the end of August and the beginning of September 1966, two strong magnetic disturbances occurred. As the satellite had the ideal situation of being in the protonosphere throughout its pole to pole coverage, such periods are being analysed to study the protonospheric response to geomagnetic storms. While the studies on this aspect are not yet complete, a very unmistakable and consistent effect during these disturbances has been noted. This effect has been an appreciable decrease in N_e at the midlatitudes and a significant shift in the position of the "main trough" to lower latitudes. No definitive change occurs in the T_e values, however. An example of this effect is seen in Figure 4b where the data points connected by dashed lines are during a satellite pass following the magnetic disturbance of Aug. 29, 1966. The observed effect in N_e is in conformity with the plasmasphere contraction noted by Taylor et al, (1965, 1968) from ion composition measurements.

Seasonal Variations

Smoothed averages of the scatter plots of N_e and T_e in Figures 4a through 4d are grouped together in Figures 5 and 6 respectively to reveal seasonal

changes in these parame' rs. We define the period May 15-22, Aug. 24-31, Dec. 1-8, Mar. 1-8, as northern summer, fall, winter and spring respectively. There appear to be two kinds of seasonal effects in N_e, one related to the hemispherical asymmetry and the other affecting the general level of electron concentration at these altitudes. The asymmetry appears as an enhancement in the summer hemisphere and is especially evident in the December measurements. The general level of N_e is lowest at equinox and highest at solstice. The significant enhancement between fall 1966 and spring 1967 may reflect the rapid increase of solar activity in early 1967. The average 10.7 cm solar flux index was 128 units in the fall period of 1966 and 184 units in the spring period of 1967. A similar explanation of the high values of N_e observed in De 'ember 1966 is not possible, however, since the rapid rise in solar activity did not occur until later.

In contrast to the large seasonal changes in N_e, the variations of T_e are comparatively small. A minor enhancement of T_e in the winter hemisphere can be noted, but there is reasonable symmetry about the magnetic equator in T_e both during fall and spring.

Although the periods adjacent to those selecte. for analysis did not have the id al location of apogee over the equator, the same seasonal effects were evident. Therefore the relatively short periods of observations employed (one week) are believed to adequately resolve the true seasonal variations.

Comparison with Explorer XXII

As the probe experiment on the Explorer XXII satellite (launched Oct. 1964, 1000 Km near-circular orbit) was also operating at the time of Alouette-II

measurements, it was possible to compare the T_e and N_e values at the 1000 Km level and the Alouette-II altitude (2500 ± 500 Km). The summer 1966 period was especially valuable because the orbit planes of the two satellites were nearly parallel and therefore the measurements corresponded to similar local times. Such comparisons are used here to obtain estimates of the temperature gradient and electron scale height between these two altitudes. The point measurements from Explorer XXII in this period are shown in Figure 7. In this satellite measurements are taken at 3-minute intervals, and consecutive points from individual passes are connected in the figure.

The average latitudinal distributions of N_e and T_e are compared in Figures 8 and 9 respectively. The Explorer XXII measurements are for the local times 22-24 hours and the Alouette-II for 0-2 hours. As there is no significant diurnal variation in these parameters at the 1000 Km altitude between 22-24 and 0-2 hours (Brace et al, 1967), these measurements can be considered nearly simultaneous. It can be noted that the latitudinal profiles at the two altitudes are similar except for their absolute magnitude. In the section that follows we shall use these profiles to obtain temperature gradients and electron scale heights between the two altitudes.

DISCUSSION

Temperature Gradient

From Figure 9 we have derived the temperature gradient along the field line between 1000 and 2500 Km by assuming that the heat conducted downwards

is independent of altitude. This should be a reasonable assumption during the nighttime when no other source of energy (other than the heat stored in the protonosphere) is expected to exist at the low and mid latitudes. This assumption implies that

$$T_e^{5/2} \frac{\partial T_e}{\partial s} = \text{constant} \tag{1}$$

Here $\partial T_e/\partial s$ is the temperature gradient at the field length s. Equation (1) can thus be used to construct T_e profile along the field line between the two satellite altitudes. One such profile, corresponding to a field line latitude of 50° N, is shown in Figure 10. Thomson scatter measurements of T_e at Millstone Hill (53° N geomagnetic) are also shown for comparison. These measurements were taken during July 1963 (Evans 1966), and thus correspond to a period of comparable solar activity.

The temperature gradients at 1000 and 2000 Km for various field line latitudes are given in Table 1. It can be noted that the T_e gradient increases significantly with latitude.

Hydrostatic Equilibrium in the Protonosphere

The question arises whether the T_e and N_e measurements at the two altitudes are mutually consistent with a hydrostatic equilibrium model of the topside ionosphere. We test this consistency by adopting the Explorer XXII values of T_e and N_e, and the derived T_e gradients, to calculate the values of N_e at

the Alouette-II altitudes. The familiar hydrostatic equation is

$$N_e = N_0 \, e^{-(h-h_0)/H} \tag{2}$$

where N_0 is the electron concentration at the Explorer XXII altitude h_0, N_e the electron concentration at a height h and H the plasma scale height given as (Smith and Kaiser, 1967)

$$H = \frac{1.7\left(\frac{T_e + T_i}{2}\right)}{M_+ + 0.85\left(\frac{h}{R_0} + 1\right)^2 \frac{\partial}{\partial s}\left(T_e + T_i\right)} \tag{3}$$

Here

T_e, T_i = electron, ion temperature

M_+ = Mean ion is mass in A.M.U.

R_0 = Earth's radius.

Employing the T_e and $\partial T_e/\partial s$ calculated from equation (1) and using equations (2) and (3) we have calculated both H and N_e at various heights up to the Alouette-II altitude. We have assumed that T_i is equal to the observed T_e and that protons are the only ions at these altitudes. The calculated values on N_e at the Alouette-II altitude are plotted as crosses in Figure 11 and are compared with the observed Alouette-II values. The dashes in the figure represent the field lines connecting the two satellite altitudes. It can be noted that there is reasonable agreement

between the observed and calculated values thus suggesting that hydrostatic equilibrium prevails in the protonosphere.

Due to the latitudinal variation in T_e and $\partial T_e/\partial s$ one should also expect a considerable variation in the plasma scale height H. The calculated values of H at 1000 Km and 2000 Km for various field tubes are given in Table 1. The latitudinal variation in H can be noted.

Thermal Balance in the Nighttime Protonosphere

It is now believed that the protonosphere is heated in the daytime by the fast photoelectrons escaping the F-region along the magnetic field lines (see e.g. Hanson, 1963). At night as the heat source is removed, the hot electrons cool by electron heat conduction downward to the F-region where the electrons and ions can lose energy by collisions with the highly abundant neutral particles. As the rate of conduction is strongly determined by T_e, the cooling becomes self limiting, and consequently the temperature of the protonosphere is governed by the thermal energy stored there (Geisler and Bowhill, 1965). To see whether the observed temperatures could be maintained throughout the night by this means, we compare the thermal energy stored in the protonosphere with the total energy conducted out of the protonosphere at night.

The thermal energy in the protonospheric field tube which could be conducted to lower altitudes is given by:

$$U = 3k\ (T_e - T_n)\ N_t \tag{4}$$

where k is the Boltzmann's constant, N_t the total electron content of the field tube, T_e the common ion-electron temperature and T_n the temperature of the neutral atmosphere. The quantity N_t above the 1000 Km altitude was calculated from the volume of the tube, V_m, and the proton concentration inside the tube. We have taken the values of V_m for various latitudes from Hanson and Ortenburger (1961). The proton concentration inside the tube has been taken as the concentration at the equatorial crossing of the field tube and is an average of various measurements by Taylor et al (1965, 1968) and Brinton et al (19[illegible]). Taking into account the T_e gradient observed at Alouette-II altitude, we have estimated T_e as 7000°, 6000, and 2800°K at the equatorial crossing of the 60°, 50° and 40° field tubes. The neutral temperature has been assumed to be 800°K. The calculated values of U, the volume of the tube V_m, and the proton concentration at the equatorial crossing $n(H^+)$, are given for various latitudes in Table 2.

The energy conducted out of the protonosphere by the electrons is given by

$$Q_e = K_e \frac{\partial T_e}{\partial s} \qquad (5)$$

The thermal conductivity, K_e, is normally written as:

$$K_e = 7.7 \times 10^5 \times T_e^{5/2} \ \mathrm{ev/cm^2/sec/^\circ K} \qquad (6)$$

We have used equations 5 and 6 to calculate Q_c for the summer 1966 data from the derived temperature and temperature gradients. The calculated values of Q_c are also given in Table 2. These refer to northern latitudes. The values for the southern latitudes were about the same, however.

The shortest field line which is crossed by both satellites corresponds to 35° latitude. This is the 2500 Km equatorial field tube. The calculated values of U and Q_c for this tube are also entered in Table 2.

The time constant, Δt, or the time for which the observed temperatures can be maintained during the night (also shown in Table 2), have been obtained by simple division of the quantity U by Q_c. These "time constants," are however, lower limits for two reasons. Firstly, because of the 5/2 power dependence on T_e, the thermal conductivity is reduced drastically during the night as T_e decreases. Secondly the tubular content has been obtained by using the value of proton concentration at the equatorial crossing, which is the lowest concentration along the tube. Nevertheless from Table 2 it can be concluded that the electron temperatures observed during the night on Alouette-II can be reasonably maintained on the basis of thermal energy stored in the protonosphere.

It should be pointed out that a theoretical investigation of the time-dependent nighttime behavior of the protonosphere has recently been reported by Nagy et al (1968). They have also shown that the total energy conducted down from the protonosphere is sufficient to maintain the electron temperature above that of the neutrals in the upper F-region. The time-dependent temperature profiles

calculated by them for midnight are in reasonable agreement with our measurements. There is also excellent agreement between the heat conduction rates calculated by them for various field tubes with those obtained from our observations (Table 2).

CONCLUSIONS

The Alouette-II and Explorer XXII electrostatic probe measurements of T_e and N_e in the nighttime protonosphere lead to the following major conclusions.

1. Significant seasonal changes at the 2500 Km altitude occur in the electron concentration, with values highest in local summer and lowest in equinox. The electron temperature, on the other hand shows no definitive seasonal dependence.

2. The temperatures at both 1000 Km and 2500 Km are consistent in terms of the thermal energy stored in the protonosphere and therefore no external source of heat is required to explain the observations.

3. The electron concentrations observed at both 1000 Km and 2500 Km are consistent with hydrostatic equilibrium in the protonosphere at the observed temperatures.

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Table 1

Field Line Latitude	Temperature Gradient (Degrees/Km)		Scale Height (Km)	
	At 1000 Km	At 2000 Km	At 1000 Km	At 2000 Km
60°	2.03	0.67	566	1678
50°	1.24	0.48	672	1583
40°	0.74	0.33	766	1450
35°	0.61	0.29	827	1428
-35°	0.39	0.23	1177	1608
-40°	0.59	0.32	1090	1685
-50°	0.70	0.40	1354	2010

Table 2

Field Line Latitude	V_m cm^3/cm^2	$n(H^+)$ cm^{-3}	U $ev/cm^2/°K$	Q_c $ev/cm^2/sec/°K$	Δt hours
35°	3.0×10^9	6×10^3	4.6×10^{12}	2.1×10^8	6.1
40°	5×10^9	4×10^3	1.0×10^{13}	2.9×10^8	10.5
50°	1.5×10^{10}	3×10^3	5.8×10^{13}	8.4×10^8	19.2
60°	2.0×10^{11}	1×10^3	3.1×10^{14}	2.4×10^9	36.0

LEGENDS TO THE FIGURES

Figure 1 Functional block diagram showing the electronics and the mounting position of the probe on Alouette-II.

Figure 2 Locations of the STADAN tracking and telemetry stations employed by the Alouette-II Satellite.

Figure 3 Alouette-II orbits during the period May 15-22, 1966 showing the relationship between altitude, latitude and local time. It can be seen that the satellite remains in the protonosphere (2500 ± 500 Km) on the nightside of the orbit throughout most of its pole to pole passage.

Figure 4a Actual T_e and N_e data points for May 15-22, 1966. The points derived from a single pass are joined by lines to approximate the instantaneous latitudinal structure.

Figure 4b Actual T_e and N_e data points for Aug. 24-31, 1966. The dashed lines are for a pass following a geomagnetic disturbance.

Figure 4c Actual T_e and N_e data points for Dec. 1-8, 1966.

Figure 4d Actual T_e and N_e data points for Mar. 1-8, 1967.

Figure 5 Average variations of N_e in the protonosphere during four consecutive seasons.

Figure 6 Average variations of T_e in the protonosphere during four consecutive seasons.

Figure 7 Actual N_e and T_e data points during May 15-22, 1966 from Explorer XXII. The orbit planes of the two satellites were nearly parallel during this period.

Figure 8 Comparison of average T_e values from the two satellites.

Figure 9 Comparison of average N_e values from the two satellites.

Figure 10 Calculated temperature profile for 50° N field tube between Explorer XXII and Alouette-II altitudes. Energy conducted downwards has been assumed to be independent of altitude. Thomson scatter values at Millstone (Evans, 1966) are shown for comparison and a model profile of the neutral gas temperature (T_n) is also shown.

Figure 11 Comparison of the observed N_e values of the Alouette-II altitudes with those calculated under hydrostatic equilibrium (crosses) by using the Explorer XXII N_e measurements and the temperatures observed by the two satellites. The field lines connecting the two altitudes are shown as dashed lines.

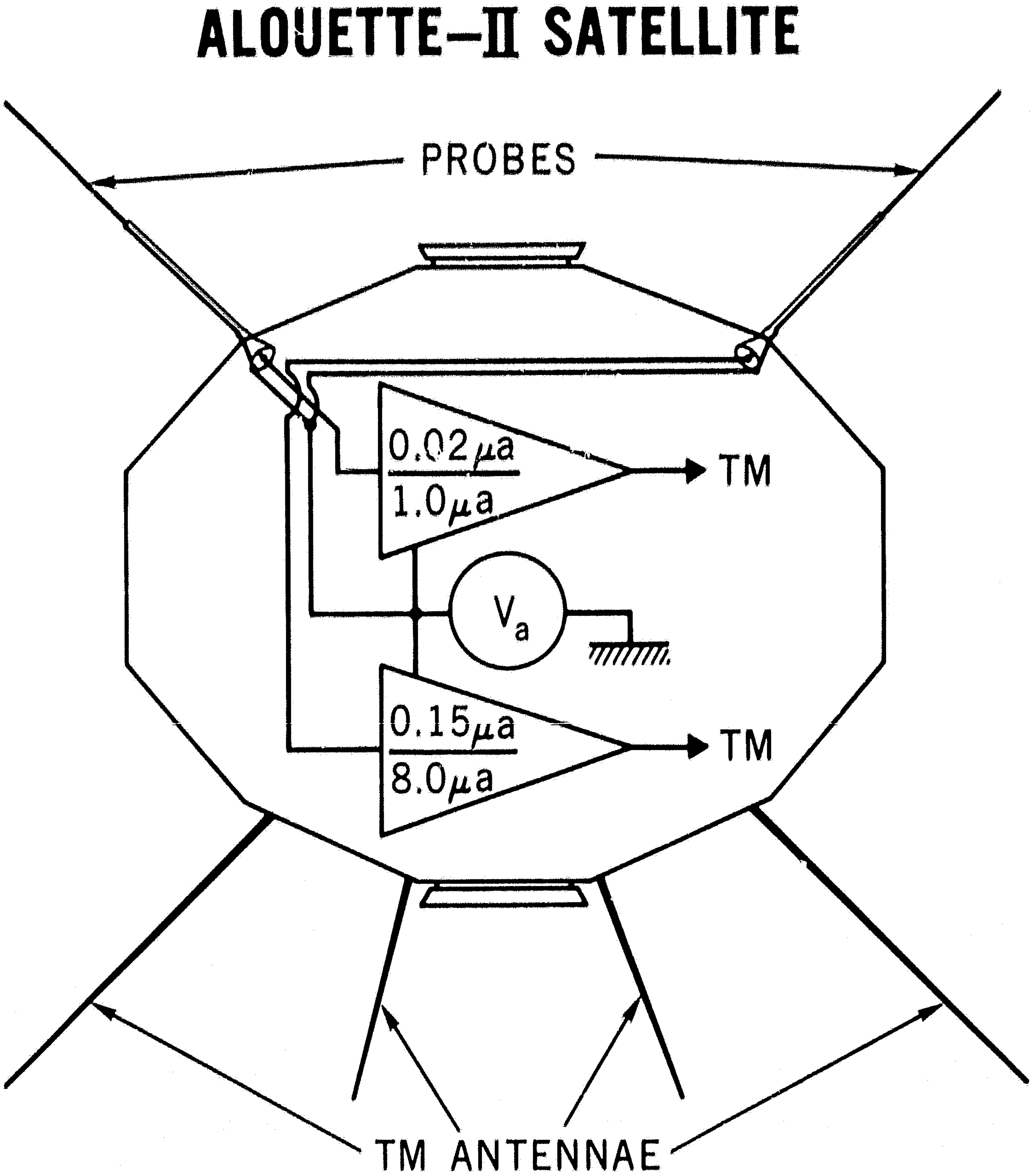

Figure 1. Functional block diagram showing the electronics and the mounting position of the probe on Alouette-II.

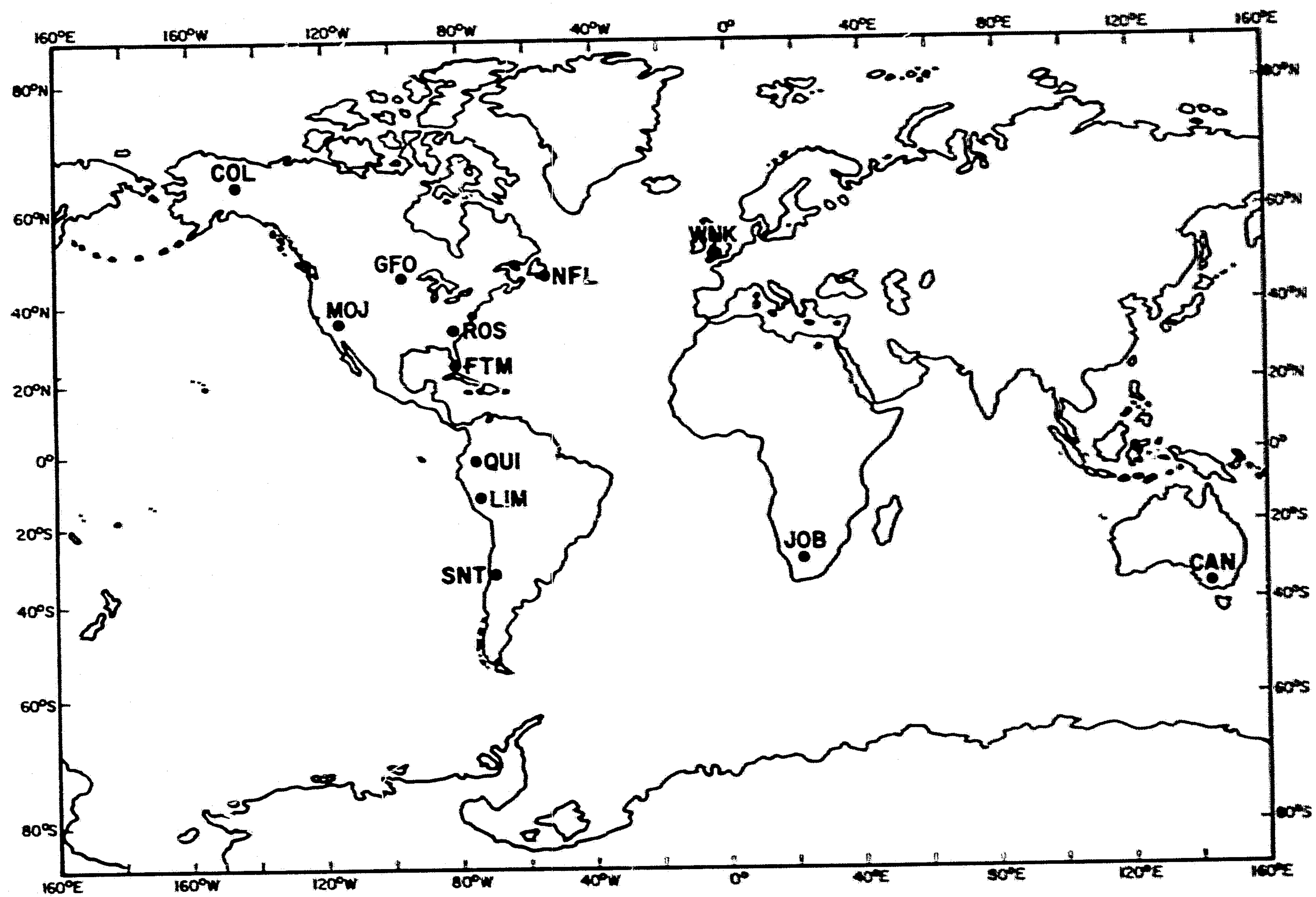

Figure 2. Locations of the STADAN tracking and telemetry stations employed by the Alouette-II Satellite.

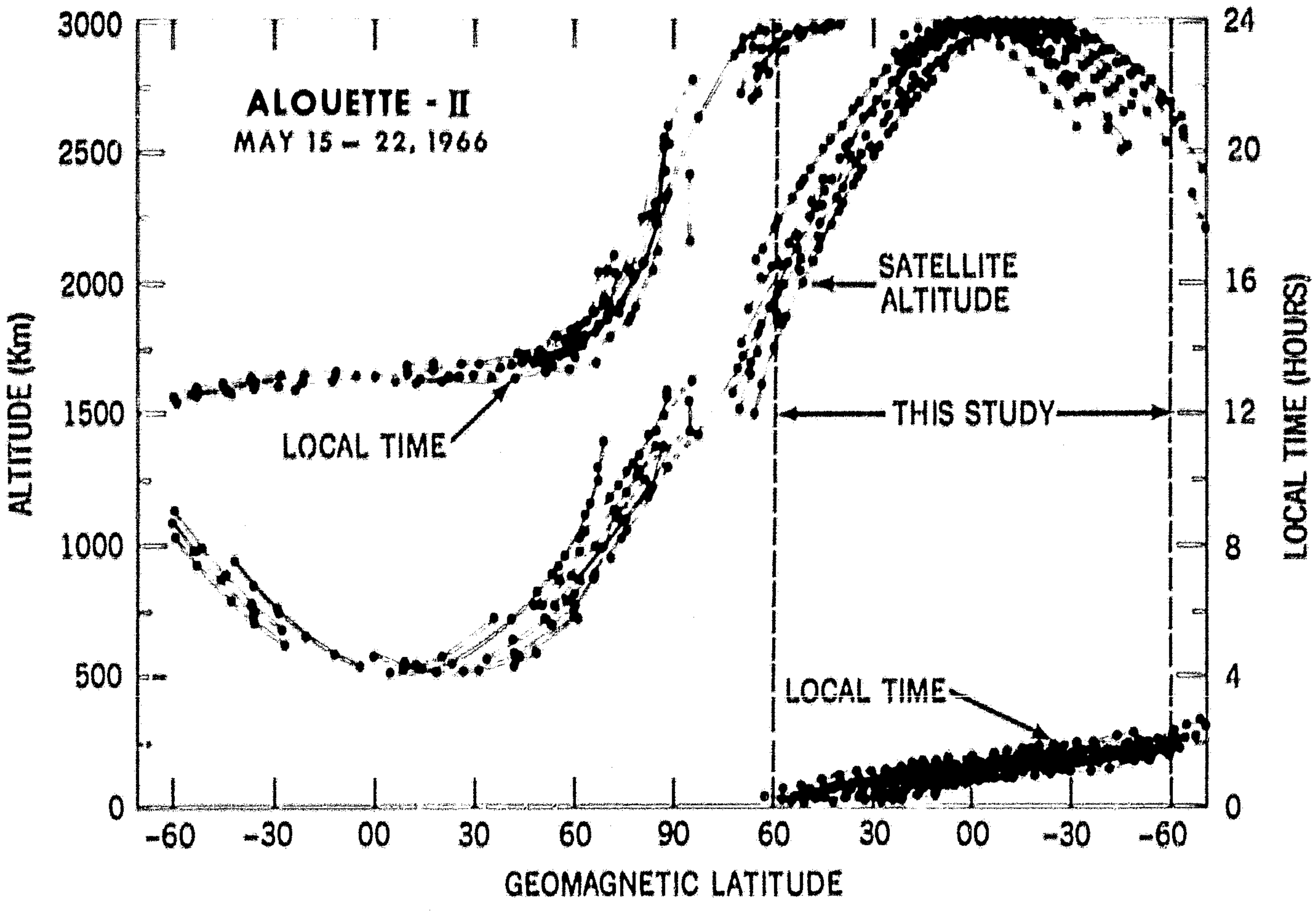

Figure 3. Alouette-II orbits during the period May 15-22, 1966 showing the relationship between altitude, latitude and local time. It can be seen that the satellite remains in the protonosphere (2500 ± 500 Km) on the nightside of the orbit throughout most of its pole to pole passage.

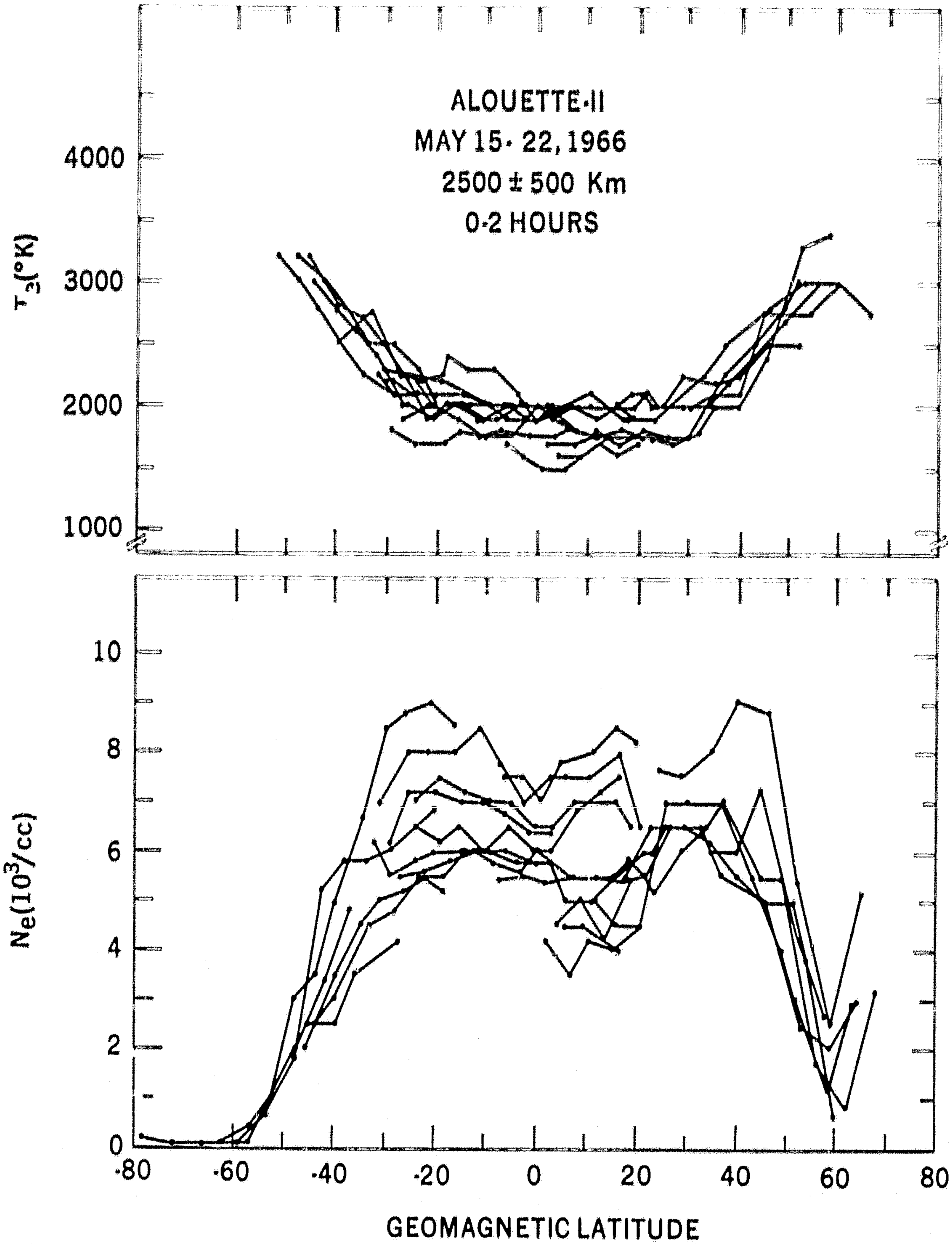

Figure 4a. Actual T_e and N_e data points for May 15-22, 1966. The points derived from a single pass are joined by lines to approximate the instantaneous latitudinal structure.

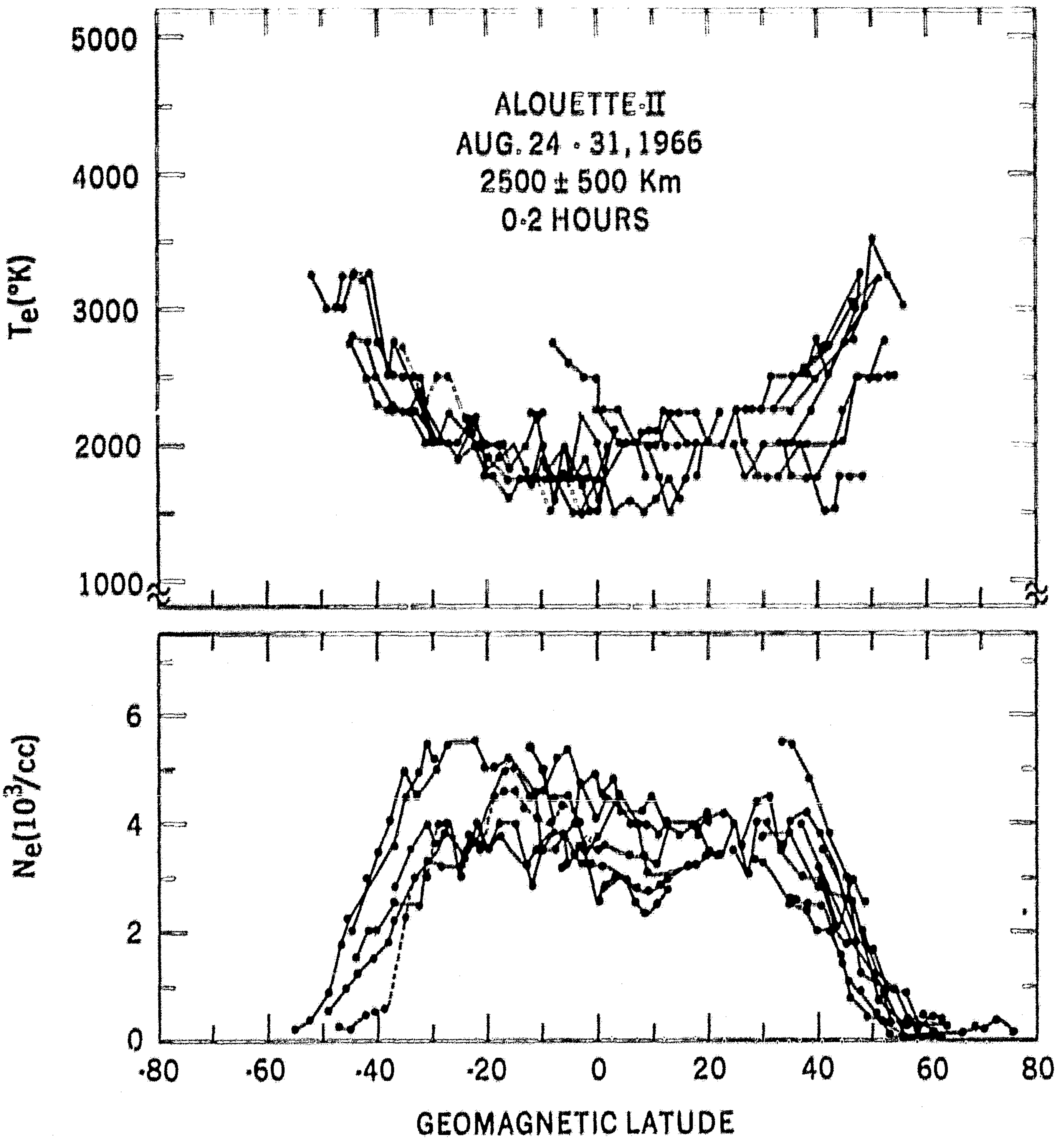

Figure 4b. Actual T_e and N_e data points for Aug. 24-31, 1966. The dashed lines in Figure 4-b are for a pass following a geomagnetic disturbance.

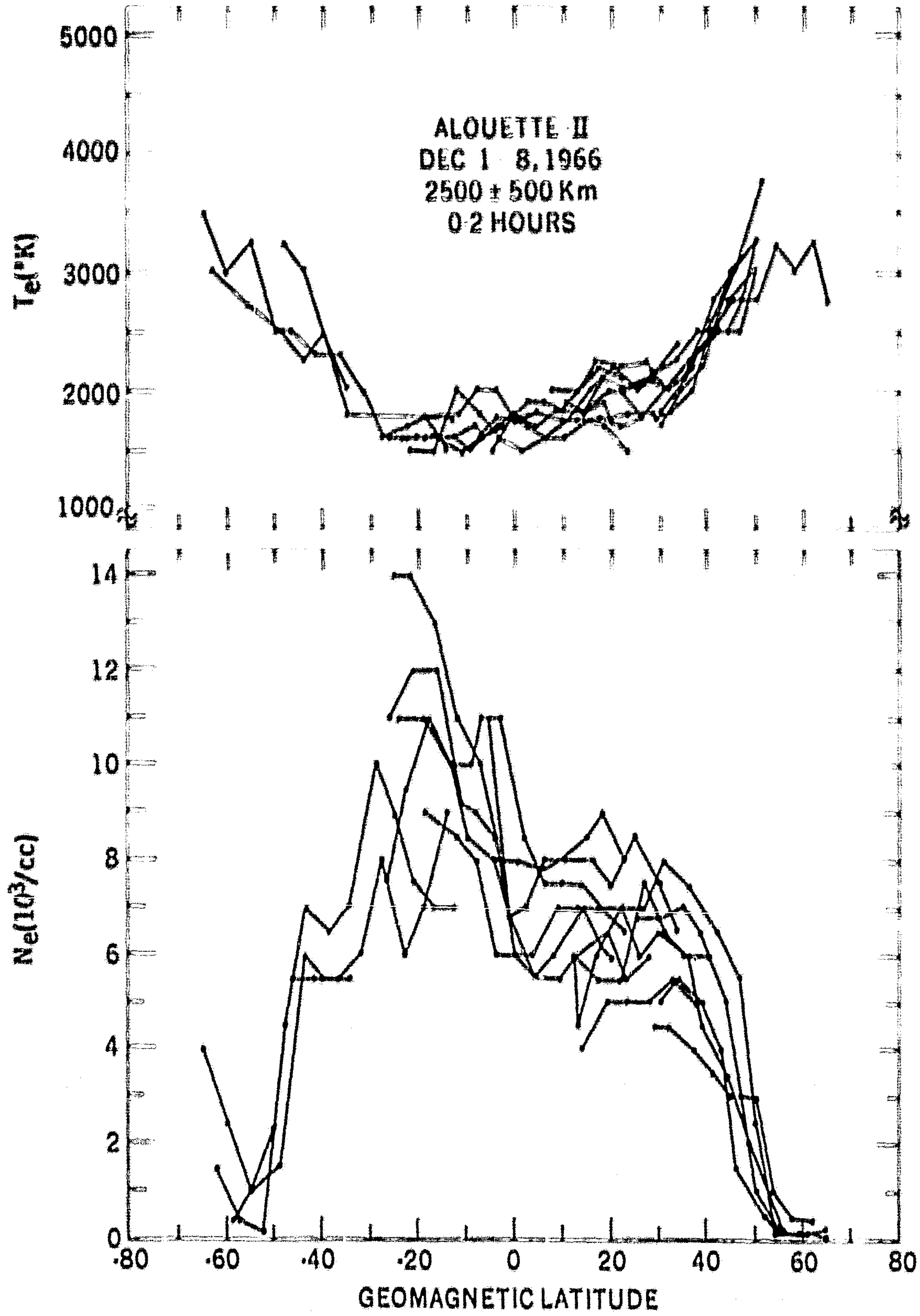

Figure 4c. Actual T_e and N_e data points for Dec. 1-8, 1966.

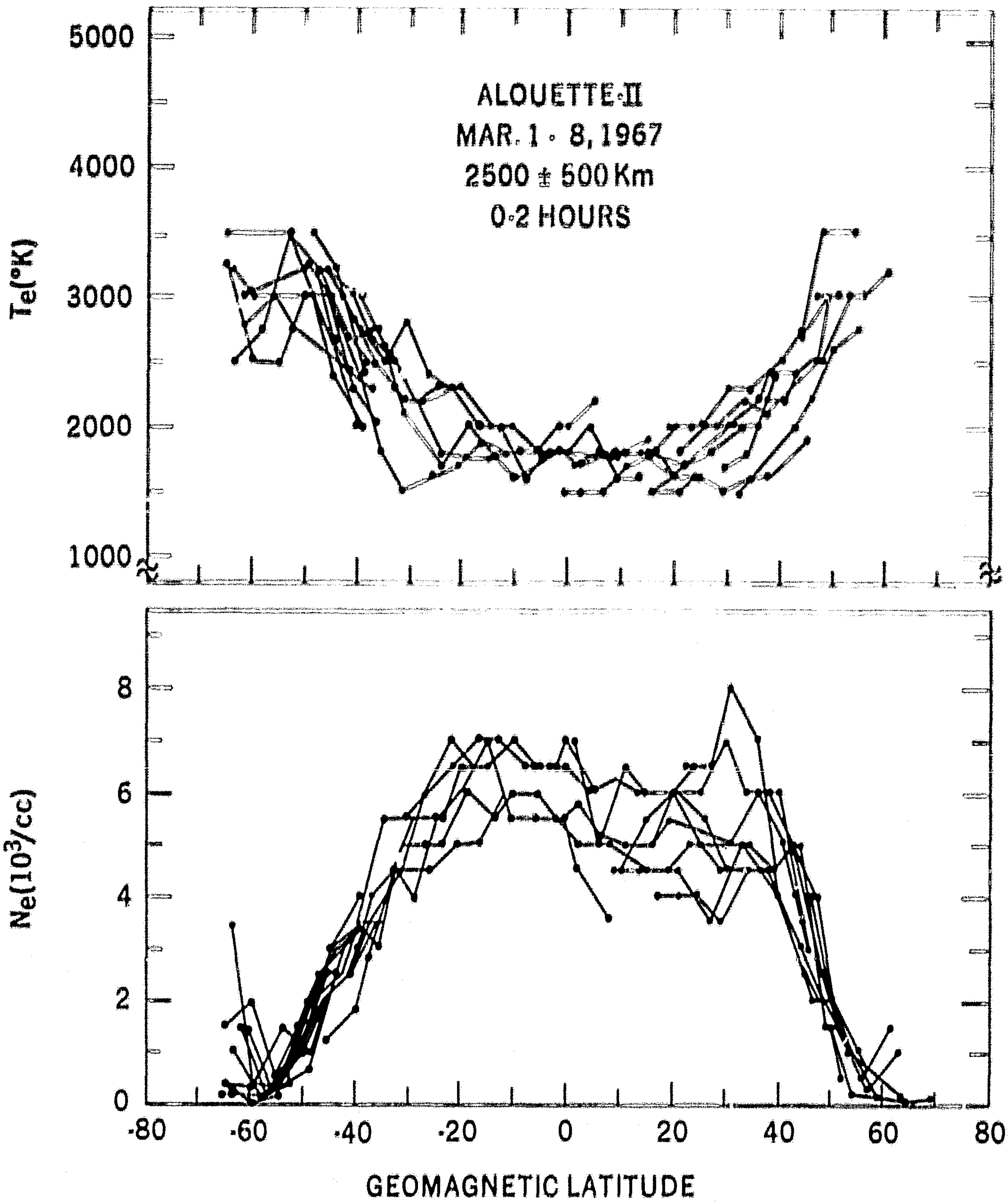

Figure 4d. Actual T_e and N_e data points for Mar. 1-8, 1967.

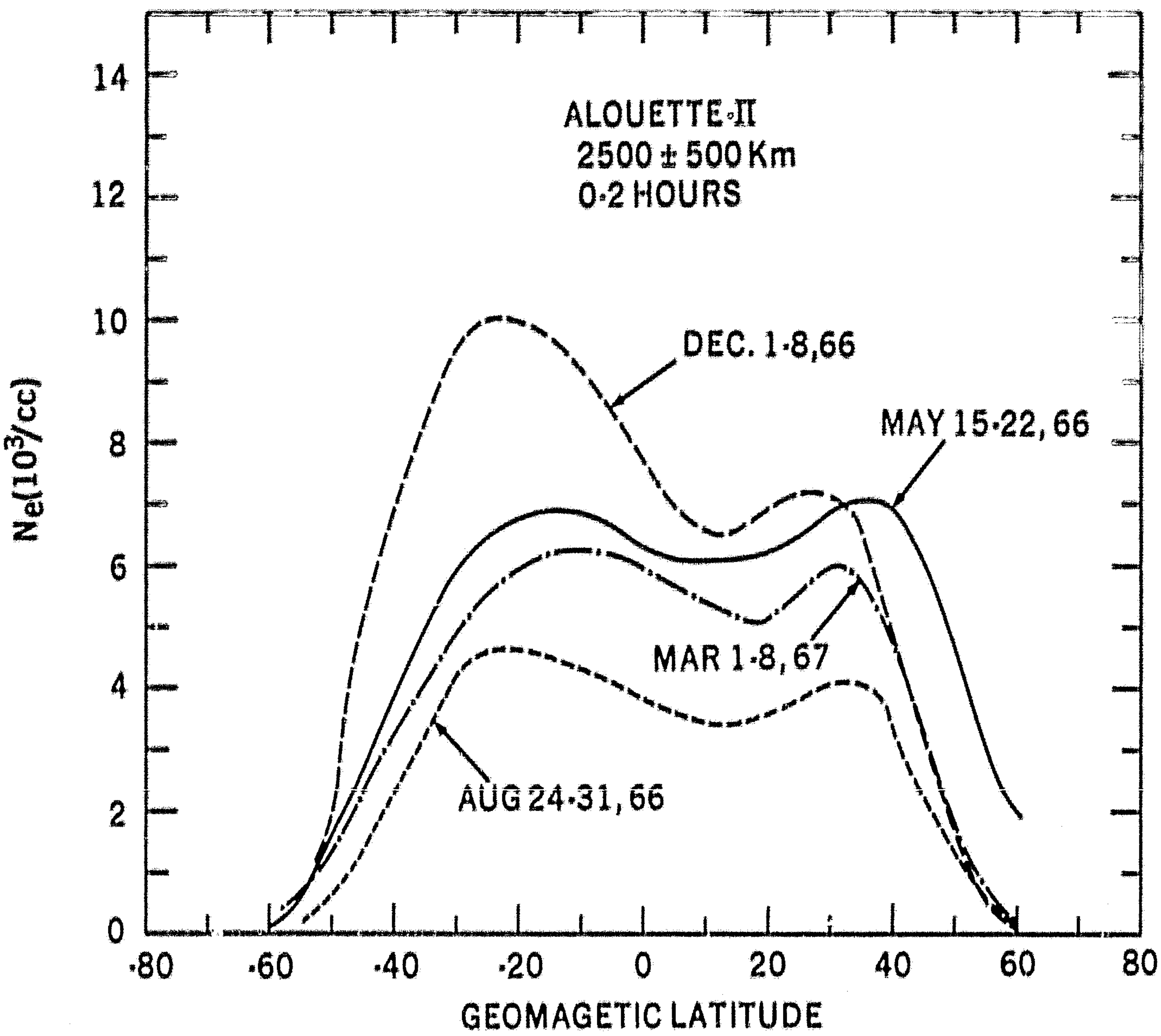

Figure 5. Average variations of N_e in the protonosphere during four consecutive seasons.

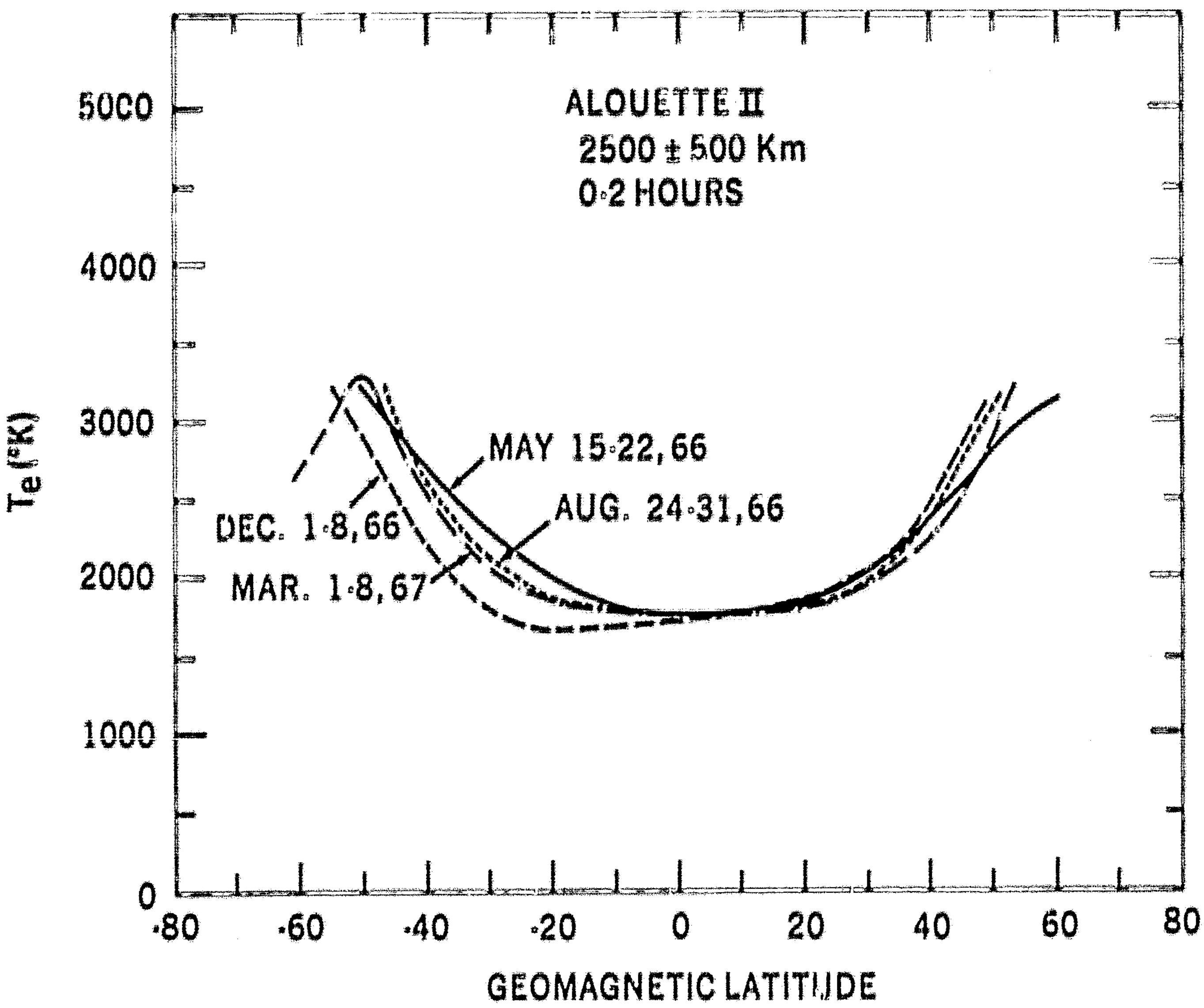

Figure 6. Average variations of T_e in the protonosphere during four consecutive seasons.

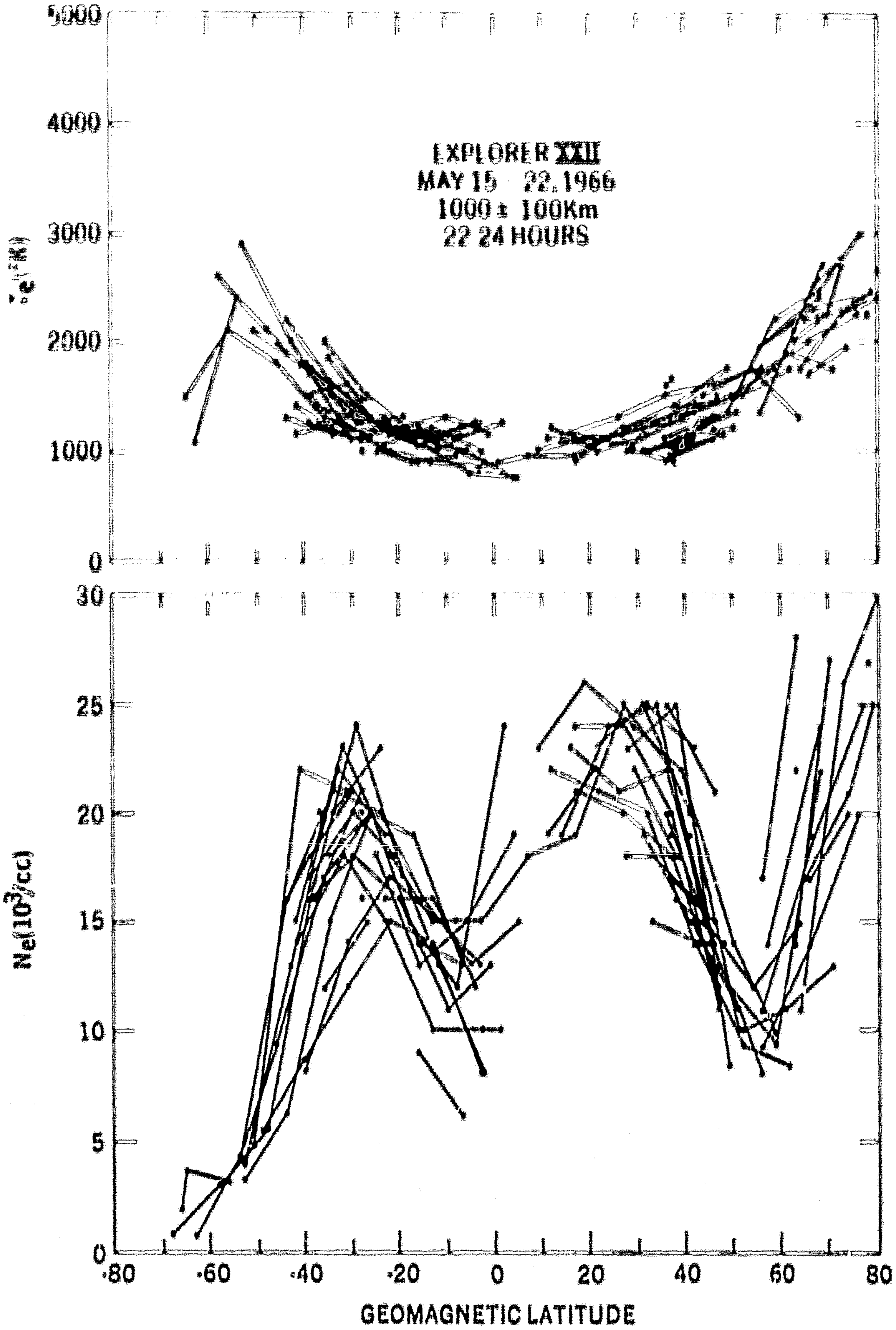

Figure 7. Actual N_e and T_e data points during May 15-22, 1966 from Explorer XXII. The orbit planes of the two satellites were nearly parallel during this period.

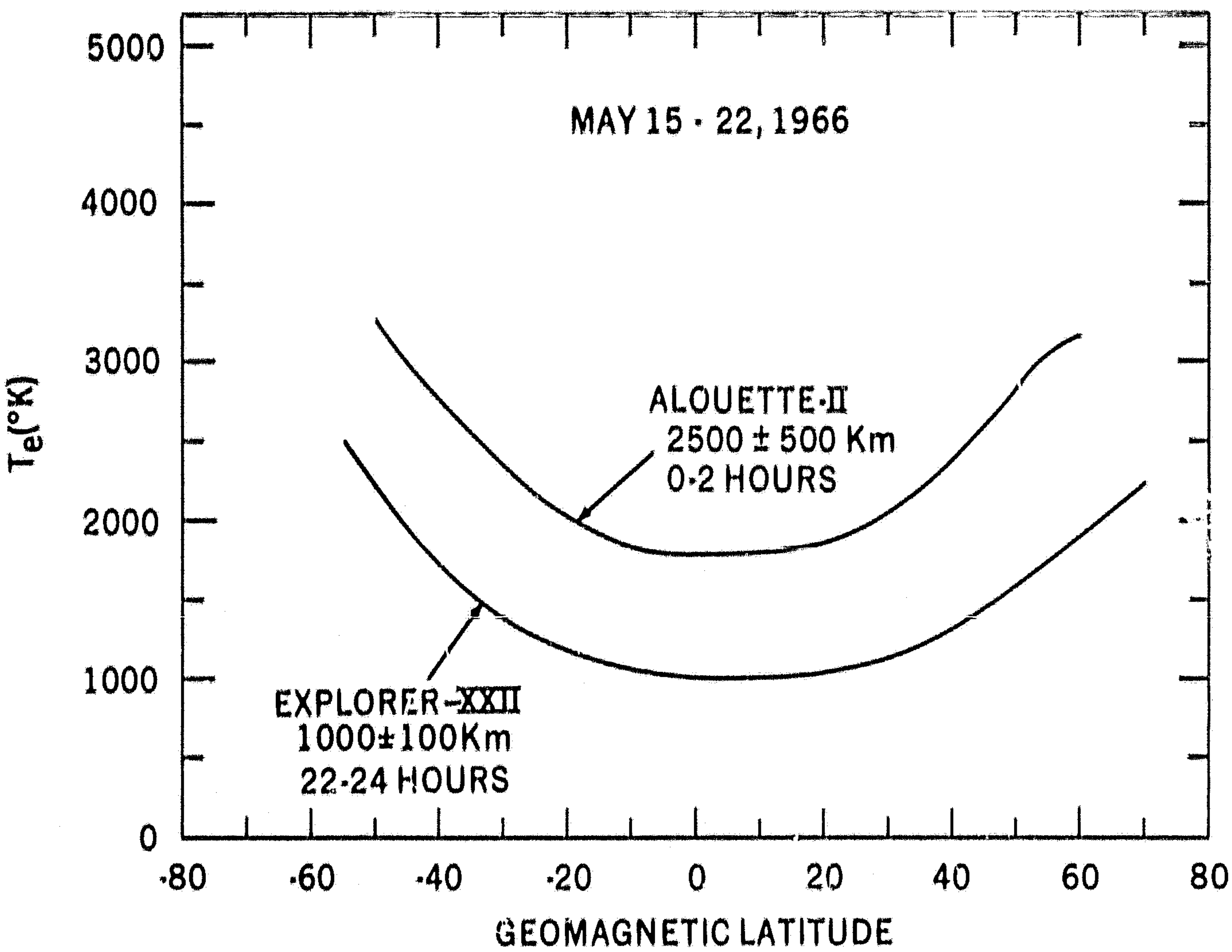

Figure 8. Comparison of average T_e values from the two satellites.

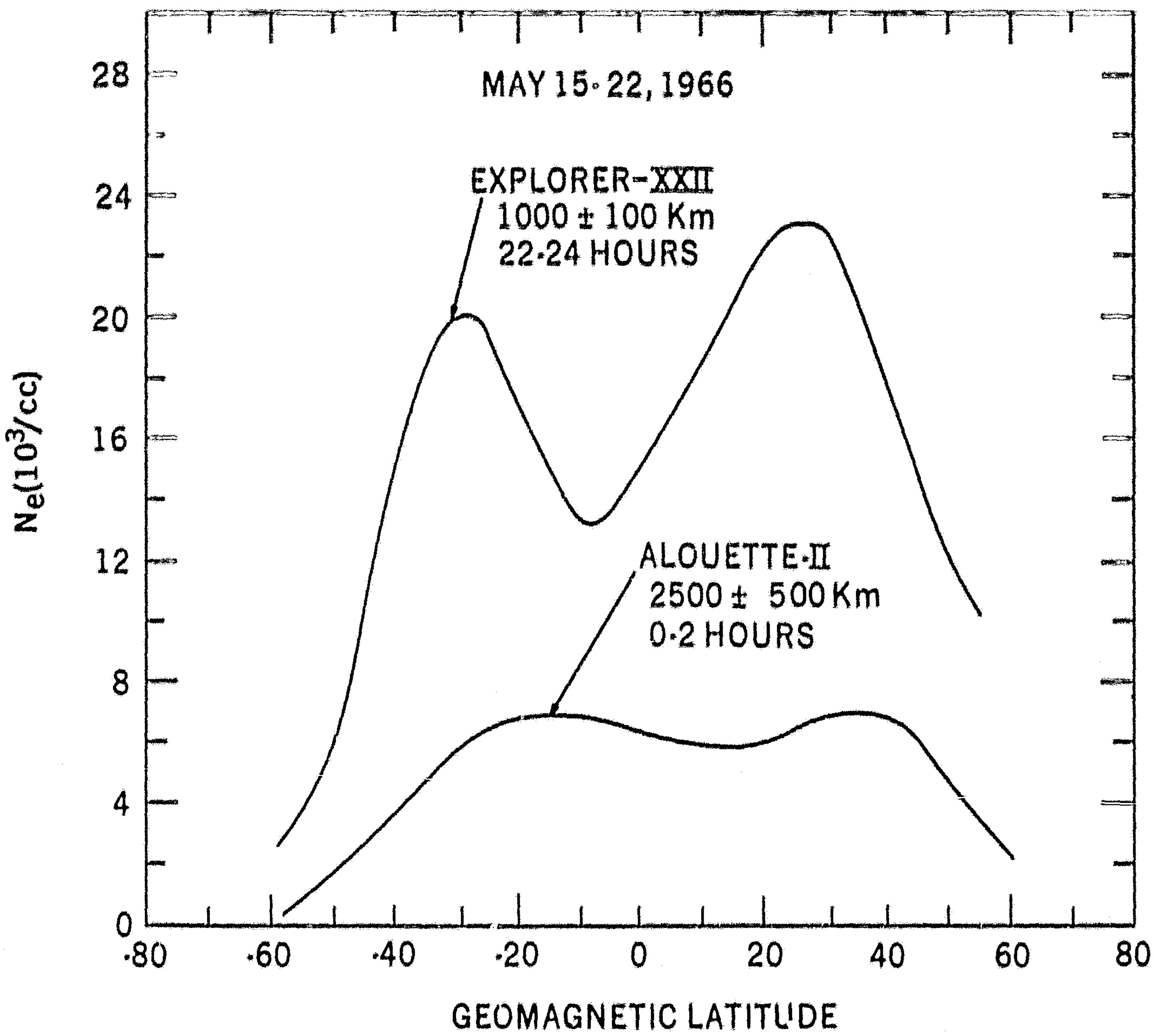

Figure 9. Comparison of average N_e values from the two satellites.

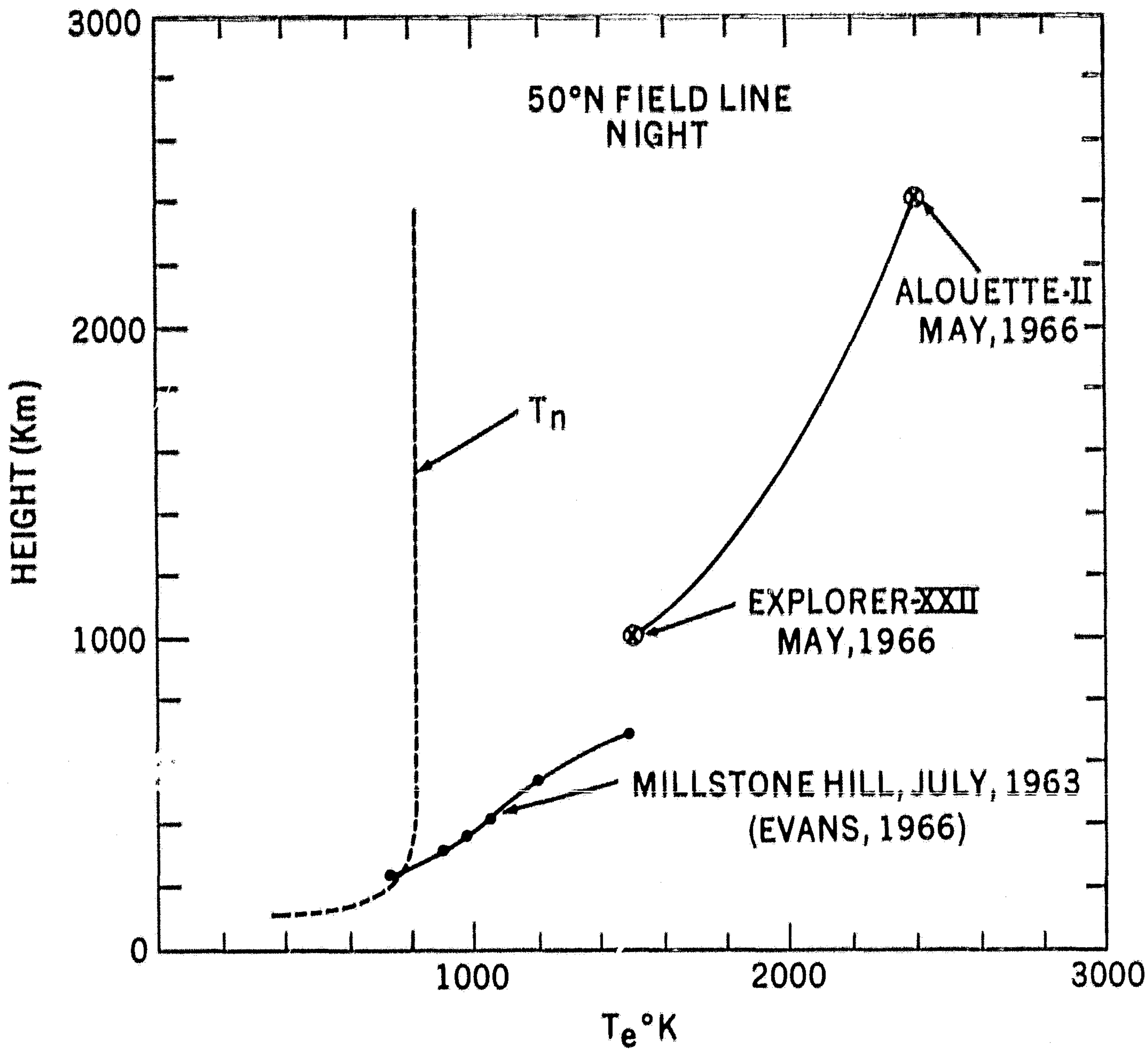

Figure 10. Calculated temperature profile for 50°N field tube between Explorer XXII and Alouette-II altitudes. Energy conducted downwards has been assumed to be independent of altitude. Thomson scatter values at Millstone (Evans, 1966) are shown for comparison and a model profile of the neutral gas temperature (T_n) is also shown.

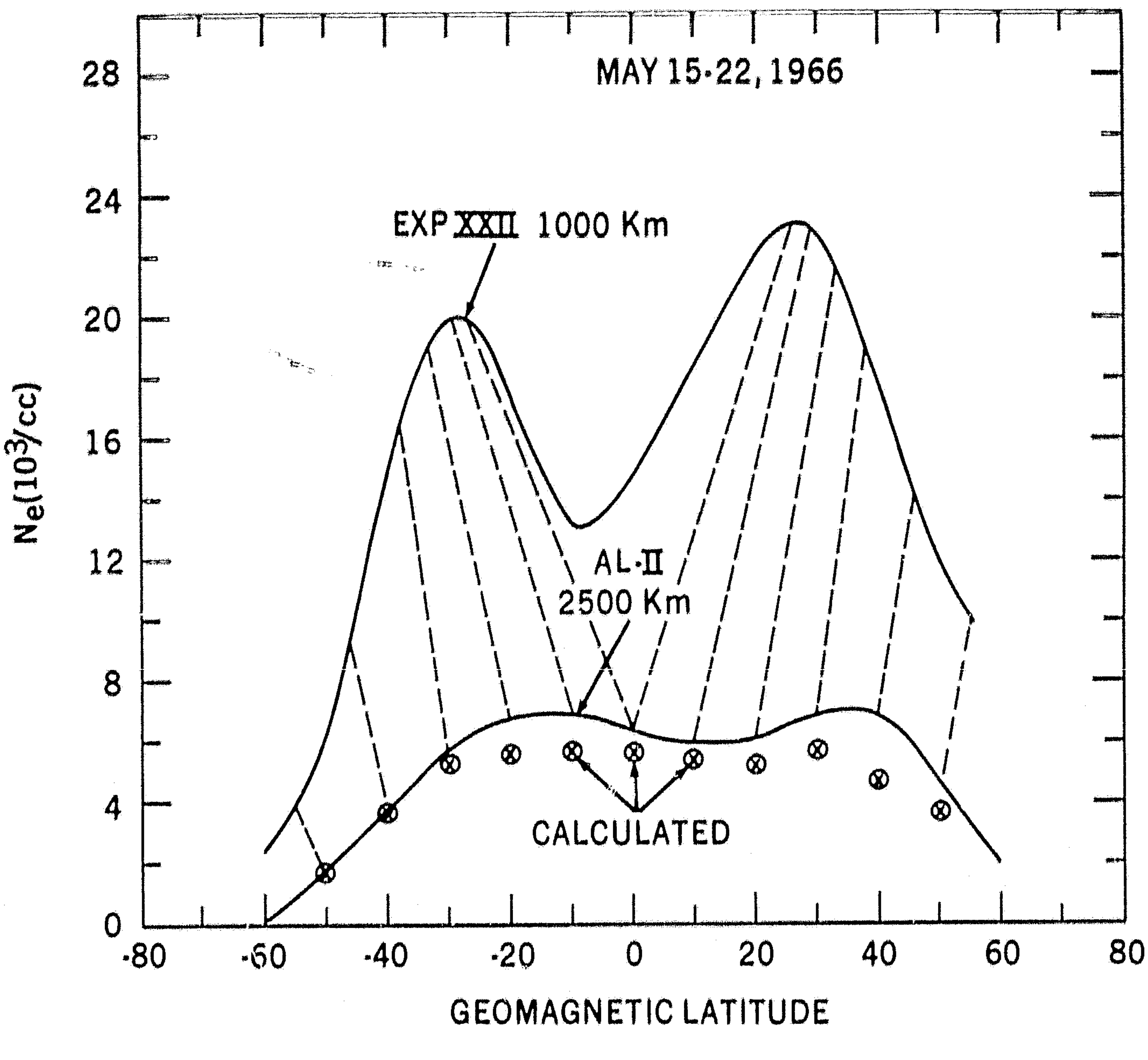

Figure 11. Comparison of the observed N_e values of the Alouette-II altitudes with those calculated under hydrostatic equilibrium (crosses) by using the Explorer XXII N_e measurements and the temperatures observed by the two satellites. The field lines connecting the two altitudes are shown as dashed lines.